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ADAPTIVE FILTERING FOR CLUTTER SUPPRESSION IN HIGH FREQUENCY RADAR

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ABSTRACT

High frequency (HF) radar has the unique potential for over-the-horizon detection of ocean surface targets. However, ocean waves are also strong reflectors for HF radar and this high clutter level has limited its application for target detection. New results from the time domain analysis of ocean clutter show that it can be modelled as two angle modulated signals; this may be used to selectively suppress the clutter component and enhance the target detection performance. The practical implementation of clutter suppression, based upon this model, involves tracking of multiple time-varying sinusoids. An adaptive filtering technique to track time-varying sinusoids is discussed and initial results presented.

I. INTRODUCTION

High frequency (HF) electromagnetic waves, propagating along the ocean surface in the ground-wave mode, are strongly reflected by certain ocean waves. Crombie [1] first observed this effect and attributed the dominant component of returned energy to back-scattering from ocean waves having a wavelength half that of the radar wavelength. Two sets of such ocean waves, moving radially to and away from the transmission site respectively, behave as diffraction gratings and cause constructive interference of the scattering returns. These scattering returns exhibit two distinct Doppler frequencies corresponding to the characteristic velocity of propagation of the two sets of ocean waves. Fig. 1 shows these two 'Bragg' scattering frequencies for an HF radar operating at 25.4 MHz; at this frequency the 'Bragg' scattering is due to ocean gravity waves of about 5.9 m wavelength. The characteristic propagation speed of about 10.9 km/hr of these 'Bragg' waves translates to a Doppler frequency of 0.51 Hz.

In addition to the dominant 'Bragg' scattering returns, a smaller and more complicated feature of the HF radar Doppler spectrum is referred to as the 'second order' scattering. Using different approaches, Barrick [2] and Walsh [3] have derived similar analytical expressions for the ocean clutter radar cross section in the HF band. This cross section, evaluated as a function of the radar Doppler frequency, contains the first and second order scattering components and is related to the directional ocean wave-height spectrum.

The impact of ocean clutter on target detection may be appreciated by the fact that the first order clutter cross section, from 'Bragg' ocean waves travelling with the wind, is typically much stronger than the cross section of a ship target. A ship target thus cannot be detected if it is moving with a velocity close to that of the 'Bragg' waves, so that Doppler

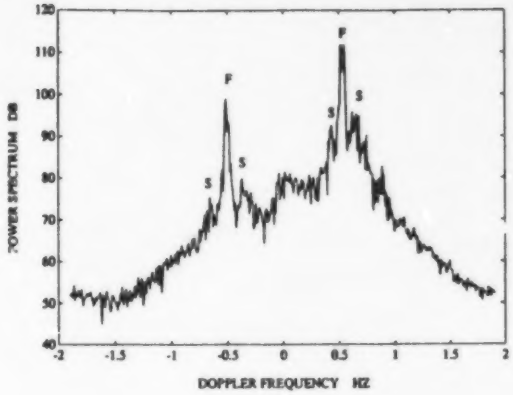

Fig. 1 Typical HF radar power spectrum showing the characteristic first- (F) and second-order (S) scattering components.

frequency discrimination is not possible. Depending on the size of the ship and the sea state, even the second order clutter cross section can mask the target. These concerns were addressed by Maresca and Barnum [4], who investigated the feasibility of detecting ships with HF radar. Their results stated, in essence, that the ocean clutter would limit target detection in significant portions of the Doppler spectrum. The resulting extent of target blind speeds would thus make such a radar device impractical.

If HF radar is to be used for low Doppler target detection, then some characteristic differences, other than Doppler frequency, between the clutter and target signals must be established. These characteristic differences could then be utilized to effect a separation of target signals from the ocean clutter signals; this would decrease or even eliminate the blind speed ranges. In an earlier publication [5], we reported that the dominant 'Bragg' ocean clutter signal exhibits some time-varying characteristics. Section II describes further detailed investigation of the time-varying behaviour of the ocean clutter and shows that the clutter can be modelled by two narrow-band signals, with time-varying frequencies, centred around the two 'Bragg' frequencies. The time varying frequency characteristic of the two narrow-band clutter signals

can be interpreted as being due to two independent angle modulations. It has been demonstrated that the spectrum of such an angle modulated signal agrees closely with the spectrum of HF radar data, and accounts for the characteristics corresponding to both the well known first- and second-order scattering peaks.

The interpretation of ocean clutter as two independent angle modulated signals allows the use of low order adaptive filters to track the clutter signals. Target detection based on this clutter model is described in Section III and involves detecting additional sinusoidal signals while tracking the clutter signals about their known 'Bragg' Doppler frequencies. In other words, the basic task in target detection is the tracking of multiple sinusoids. The following discussion assumes a single target in a given radar range cell; multiple targets may be handled by a simple extension of the analysis.

II TIME-VARYING CHARACTERISTICS OF HF OCEAN CLUTTER

This section summarizes the results of our study of the time-varying frequency characteristics of HF radar ocean clutter signals. The need to estimate signal parameters over short data segments prompted us to apply parametric and adaptive methods to these signals. Specifically, simple estimation algorithms, based on the well known technique of linear prediction, were used to establish the following characteristics of ocean clutter signals:

a) In a short time frame, the clutter signal consists essentially of two narrow-band Doppler signals only, corresponding to the two 'Bragg' scattering frequencies.

b) The frequencies of the two narrow-band Doppler signals vary with time; their average values agree with the theoretically predicted 'Bragg' Doppler frequencies.

c) A low order prediction filter, with time-varying coefficients, adequately models both the first and second order Doppler spectra.

It is well known that, at high signal-to-noise (SNR) ratios, linear prediction (LP) or auto-regression (AR) based methods can be effectively used to estimate the parameters of sinusoidal signals [6]. The prediction error filter (PEF) is an all zero filter and it can be shown that, for a signal containing M sinusoids, the transfer function of the PEF has M zeros on the unit circle at the angular locations corresponding to the angular frequencies of the M sinusoids in the signal [7]. It can also be shown that if the PEF has L zeros, where L > M, then the L-M extraneous zeros are uniformly distributed in angle around the inside of the unit circle. These properties of the PEF were used to test the hypothesis that the ocean clutter signal contains only two narrow-band sinusoids with time-varying frequencies near the Bragg frequency. During a short time frame, the number of zeros of the PEF on the unit circle determine the number of sinusoids in the signal and their angular positions determine the frequencies of the sinusoids.

To track the time-varying behaviour of the ocean clutter signal, the coefficients of the prediction error filter must be estimated using very short data segments; alternately an adaptive scheme may be implemented to continuously update their values. The roots of the PEF transfer function are evaluated at every iteration to determine the locations of the zeros. Using HF radar data from an ocean cell, at a range of 6 km, Fig. 2 is a cluster plot of 425 sets of PEF transfer function zeros computed at time intervals of 0.262144 s. The length of the prediction filter used was three and it is seen that only two zeros are clustered near the unit circle. The angular location of the cluster centres correspond to the two theoretically predicted Bragg frequencies. The location of the third cluster, well within the unit circle, denies the existence of a third sinusoid [7].

As a further test, Fig. 3 was obtained using a PEF of length 9. Again, it is seen that only two roots cluster on the unit circle confirming that the signal contains two sinusoids only. None of the remaining seven roots approach the unit circle.

Both Figs. 2 and 3 show a significant spread, in angular position, of the two roots clustered on the unit circle. The spread in angular position is directly related to the frequency variations of the corresponding sinusoids. Similar cluster plots have been obtained using a number of different HF radar data sets. These tests led to the conclusion that the ocean clutter signal contains two narrow-band sinusoids, with time-varying frequencies, centred around the theoretically predicted Bragg frequencies.

There is a direct correspondence between the angular position of the zeros of the PEF transfer function and the frequency of the sinusoid contained in the signal. Thus, by analyzing the zero locations at each iteration, the time variations of the sinusoids in the clutter signal could be established. Fig. 4 shows the estimated time variations of the frequencies of the ocean clutter signal.

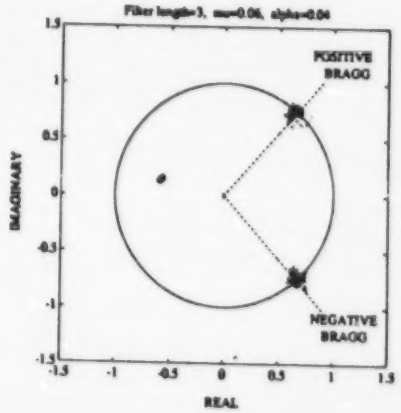

Fig. 2 Cluster plot of adaptive PEF transfer function zeros. Input to filter was HF radar data with ocean clutter signal only.

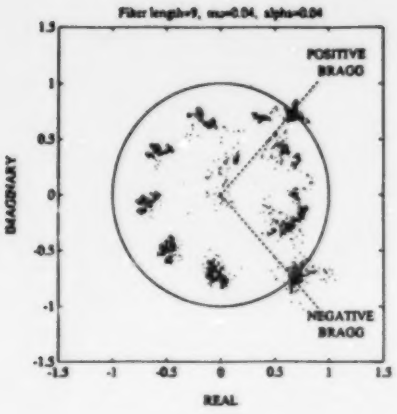

Fig. 3 Root cluster plot, similar to Fig. 2, corresponding to a higher order adaptive PEF. Only two roots cluster on unit circle indicating a signal with two sinusoids.

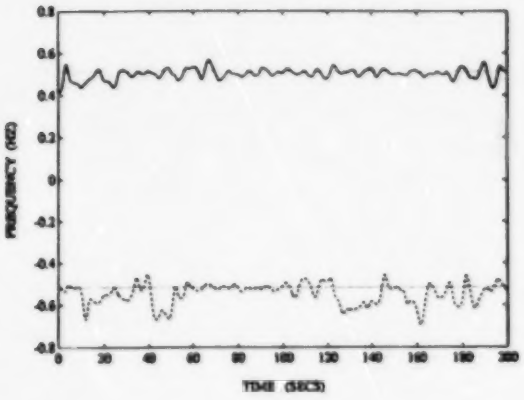

Fig. 4 Time-varying behaviour of the two dominant narrow-band frequency components in HF radar ocean clutter.

We believe that these observed frequency variations of the ocean clutter signal may contain answers to a number of questions regarding the interaction of HF radar with ocean waves and may provide insight into the fundamental behaviour of ocean waves. The first obvious interpretation of Fig. 4 is simply that the 5.9 metre ocean waves, corresponding to the Bragg frequency, are not moving with a constant velocity. Rather, possibly due to interaction with other ocean waves, their velocity is constantly changing about an average velocity. It can be easily shown that this velocity variation would cause an angle modulation of the radar Doppler return, causing the observed frequency variations. Based on this interpretation, a composite description of the ocean surface obtained using HF radars operating at different wavelengths could enhance our understanding of the ocean waves.

III. ESTIMATION OF MULTIPLE TIME-VARYING SINUSOIDS

The results of the previous section clearly show that the main characteristics of the ocean clutter signal can be easily modelled using a low order adaptive predictive filter. The parameters of the clutter signal, such as instantaneous frequency, can be accurately estimated. In the presence of a target signal, simple prediction error filtering is restricted to situations where the target Doppler frequency is well separated from the 'Bragg' Doppler frequencies. When the target Doppler approaches one of the 'Bragg' frequencies, the overall data can still be easily modelled but the errors in estimating the parameters of the individual components becomes large. If two of the signals are close to each other in frequency, the estimated magnitudes and phases of the signals are distorted with respect to the actual signals.

The ability of any structure to adapt to time-varying signals depends on the choice of error signals and the method of estimation for the various coefficient sensitivities required to update the variable coefficients in the structure. In addition, parameters controlling the adaptation and convergence rates must be matched to the characteristics of the input signal. A different approach [8] has been suggested to isolate individual signals by adaptively notching out all the other signals. As shown in Fig. 5, such a scheme for three signals could be used to track two clutter and one target signal for a single radar range cell. Problems were also reported for this scheme, when two signals were closely spaced. However, for our application where the target and clutter signals approach each other in frequency, the different characteristics of the signals allow these problems to be overcome. The scheme of Fig. 5 has been implemented using biquadratic notch filters with low order adaptive tracking filters and initial results show that real time target detection can be achieved.

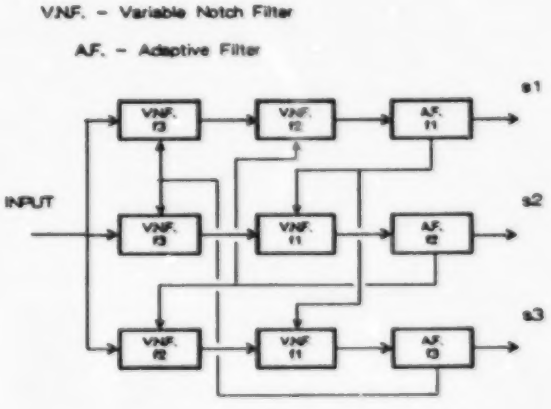

Fig. 5 Decomposition of a signal into its three components s1,s2,s3. Each adaptive filter controls the notch filters on the other two channels.

A particular data set was chosen from a ship detection experiment where the ship Doppler was close to the 'Bragg' Doppler frequency. Fig. 6a shows the spectrum of the radar data with the two clutter peaks as well as the ship target identified. It is noted that the side-band structure of one of the 'Bragg' components overlaps that of the ship signal. Fig. 6b shows the result of estimating the time behaviour of these signals using the scheme of Fig. 5. The frequency overlap is clearly visible and the 'carrier' frequencies correspond to the peaks of the spectrum in Fig. 6a.

It is expected that extensions of this simple technique presented here could result in robust real-time methods for low Doppler target detection using HF radar. The resulting improvement in signal-to-noise ratio may contribute to establishing HF radar as an effective surveillance device for over-the-horizon detection of surface targets.

IV. CONCLUSIONS

A few fundamental time domain characteristics of HF radar ocean clutter signals have been established. Specifically, it is shown that the ocean clutter may be adequately modelled with two narrow-band signals with time-varying frequencies.

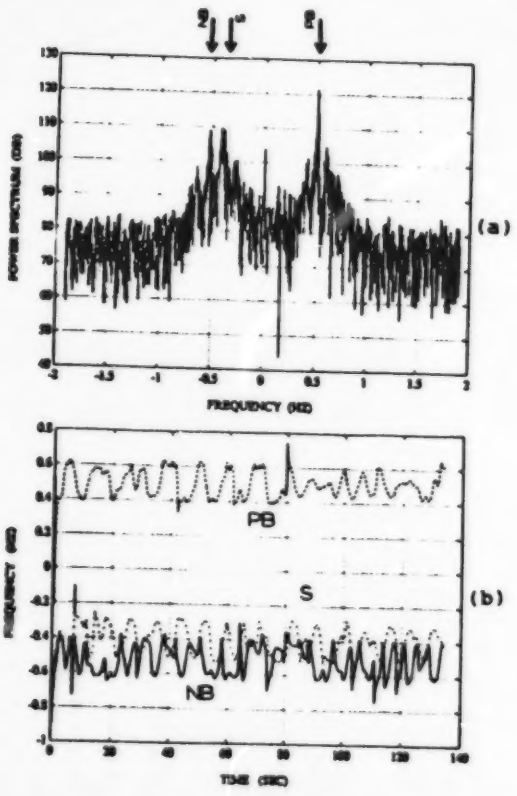

Fig. 6 a) Power spectrum of HF radar data with a ship signal and ocean clutter. b) Frequency variations of the three components estimated using the scheme of Fig. 5. (PB-positive Bragg, NB-negative Bragg, S-ship)

Low order adaptive prediction filters can thus be used to track the ocean clutter signals. Target detection is formulated in terms of detecting an additional narrow-band signal while tracking the two dominant clutter signals. A technique for tracking multiple time-varying sinusoids has been implemented and initial results presented. This technique has been chosen for its ability to perform in situations where two of the signals are close to each other in frequency.

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